Overview of Physics with High Intensity Proton Beams

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P5 Meeting @ BNL

planned
proposed

Rare Processes Explore

- New forces in nature:
  - non-Standard flavor-changing neutral currents (neutrinos, kaons); — LBNE, ORKA
  - charged-lepton flavor violation ($\mu \to e$); — Mu2e
  - baryon number violation (*n*-*ñ*, proton decay). — NNbarX, LBNE
- New properties and kinds of matter: — LBNE
  - sources of *CP* violation in neutrinos, charged leptons, quarks; — elec. dip. mom.
  - sterile neutrinos. — νSTORM
- New dimensions: — New Muon g–2
  - constraints on supersymmetry in loop diagrams ($d^4x\,d\theta\,d\bar{\theta}$); — ORKA
  - constraints on extra dimensions ($d^4x\;d^\delta y$). — LBNE

Lagrangian Will Keep Us Together

- The aim of particle physics (at any "frontier") is to understand

$$\begin{aligned}\mathscr{L} &= \mathscr{L}_{\text{SM}} + \mathscr{L}_{\nu\text{M\&M}} + \mathscr{L}_{\text{BSM}}(\text{TeV scale, dark stuff}) + \mathscr{L}_{\text{QG}} \\ &= \cdots + \mathscr{L}_{\nu\text{M\&M}} + \sum_{\mathscr{O}} \left[G_F C_{\mathscr{O}}(\text{CKM}, \alpha_s, \alpha, \sin^2\theta; \boldsymbol{x}) + G_{\mathscr{O}}(\text{BSM parameters}) \right] \mathscr{O},\end{aligned}$$

where $C_{\mathscr{O}}$ and $G_{\mathscr{O}}$ are complex (if CP violating) Wilson coefficients for operator $\mathscr{O}$,
G_F, CKM, α_s, α, $\sin^2\theta$ are SM couplings,
$\boldsymbol{x} = (m_s^2, m_c^2, m_b^2, m_t^2, M_H^2)/M_W^2$,

- Many, many operators $\mathscr{O}$:
  - over 1000 four-fermion operators;
  - plus around 40 penguin operators (including flavor violation like $\bar{\mu}\sigma \cdot Fe$).

$$G_{\mathscr{O}} = \begin{cases} \dfrac{1}{\Lambda^2} & \text{mass from gauge field} \\ \dfrac{g^2}{y^2\Lambda^2} & \text{mass from Higgs field} \end{cases}$$

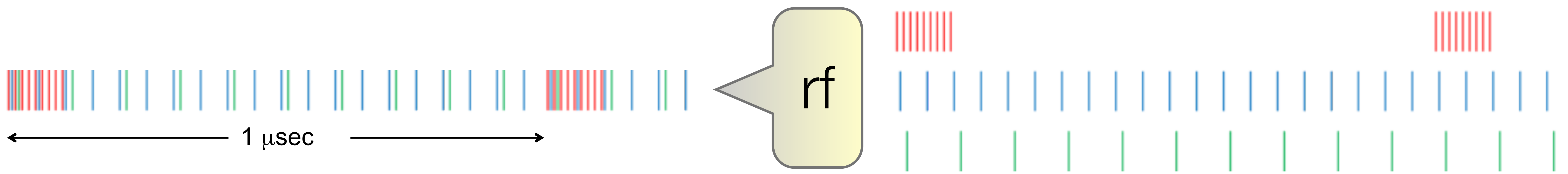
- HEP has identified several promising ways to get at the fields and/or $G_{\mathcal{O}}$:

launched
planned
proposed

  - direct production (CDF, D0; ATLAS, CMS);
  - tree-level exchange (old examples are W in νN & Z in e^+e^- before UA1 & UA2);
  - flavor-changing lepton processes:
    - neutrino oscillations (NOvA, LBNE) & non-standard neutrino interactions (LBNE);
    - charged lepton flavor violation (Mu2e);
  - FCNCs with quarks: rare kaon decays (ORKA), b-quark physics (LHCb, Belle 2);
  - CP violation: LBNE, quark flavor, electric dipole moments (Proton SR EDM), …;
  - baryon number violation: proton decay (LBNE), neutron↔antineutron (NNbarX);
  - magnetic part of photon propagator from short distances (New g–2 Experiment).
- Salient feature of rare processes is reach to higher scales Λ than with direct production.

Continuous Wave Option

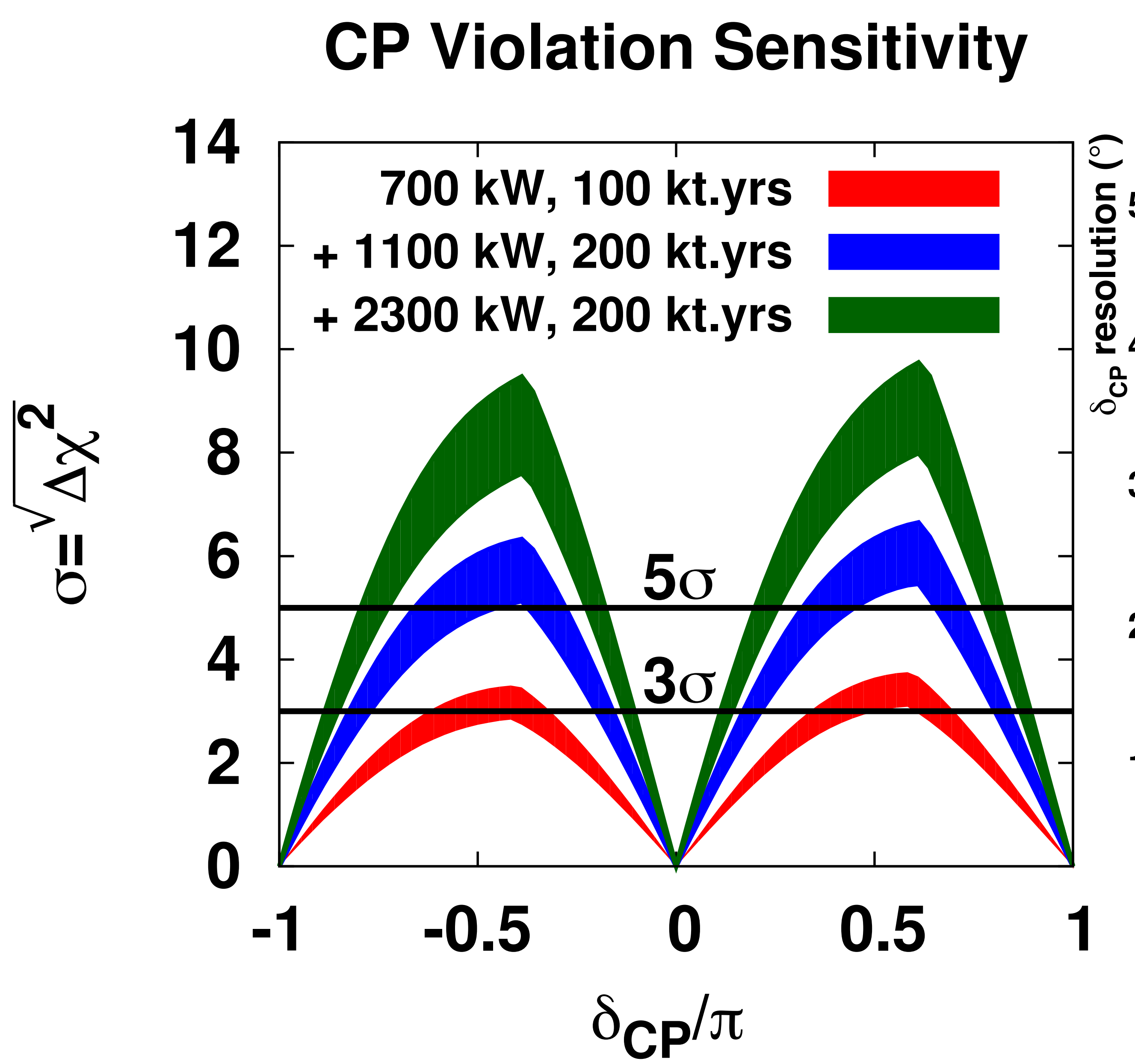
- PIP-II could be filled with several beam structures, as needed by the experiments. Example:
  - pulses for MI ν expt: 15 Hz, 4.3 ms 1200 kW
  - pulses for muon expt: 80 MHz, 100 ns 700 kW
  - pulses for kaon expt: 20 MHz 1540 kW
  - pulses for EDM expt: 10 MHz 770 kW

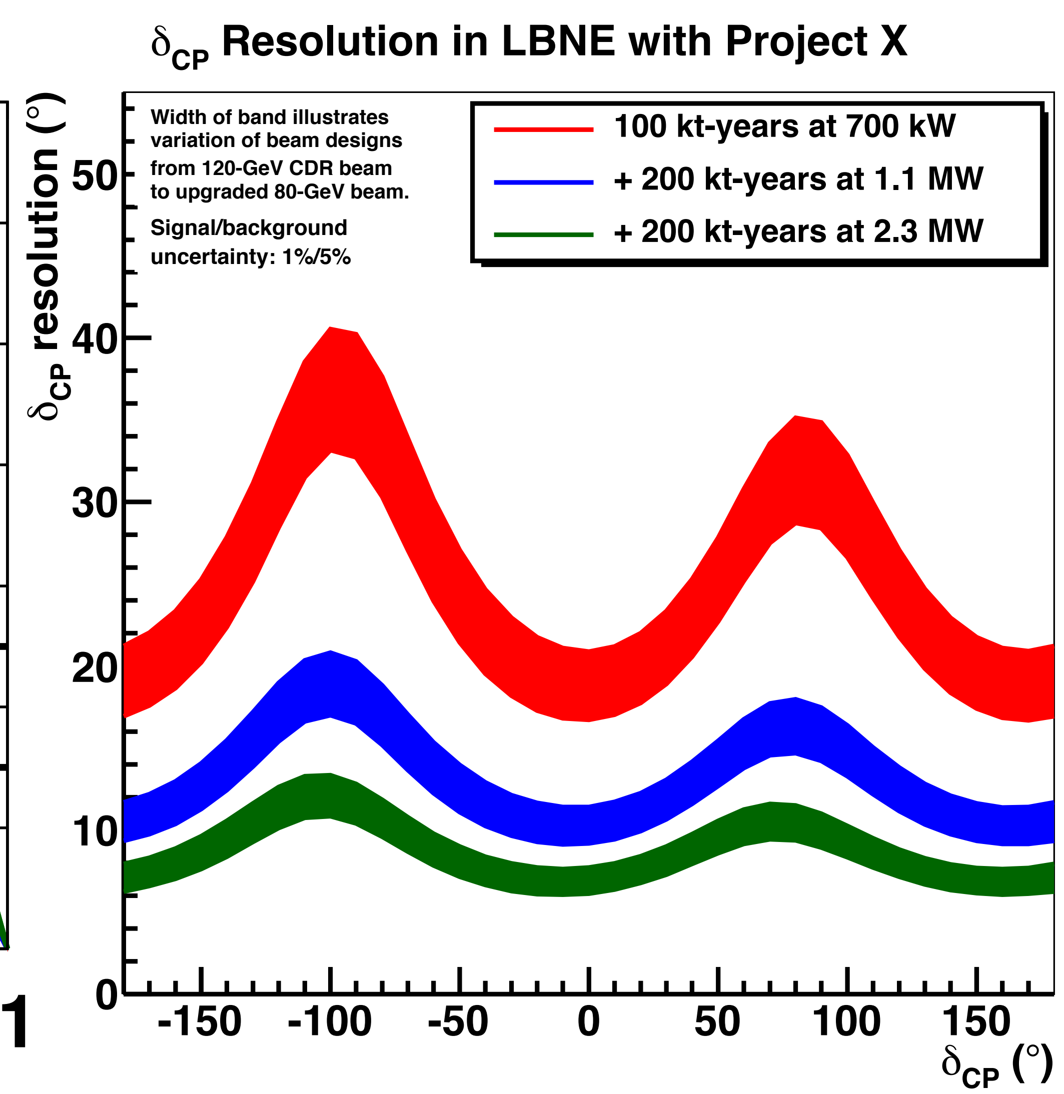


- Devised for Project X, Stages 1 & 2, but also works at PIP-II's 800 MeV.

Neutrinos

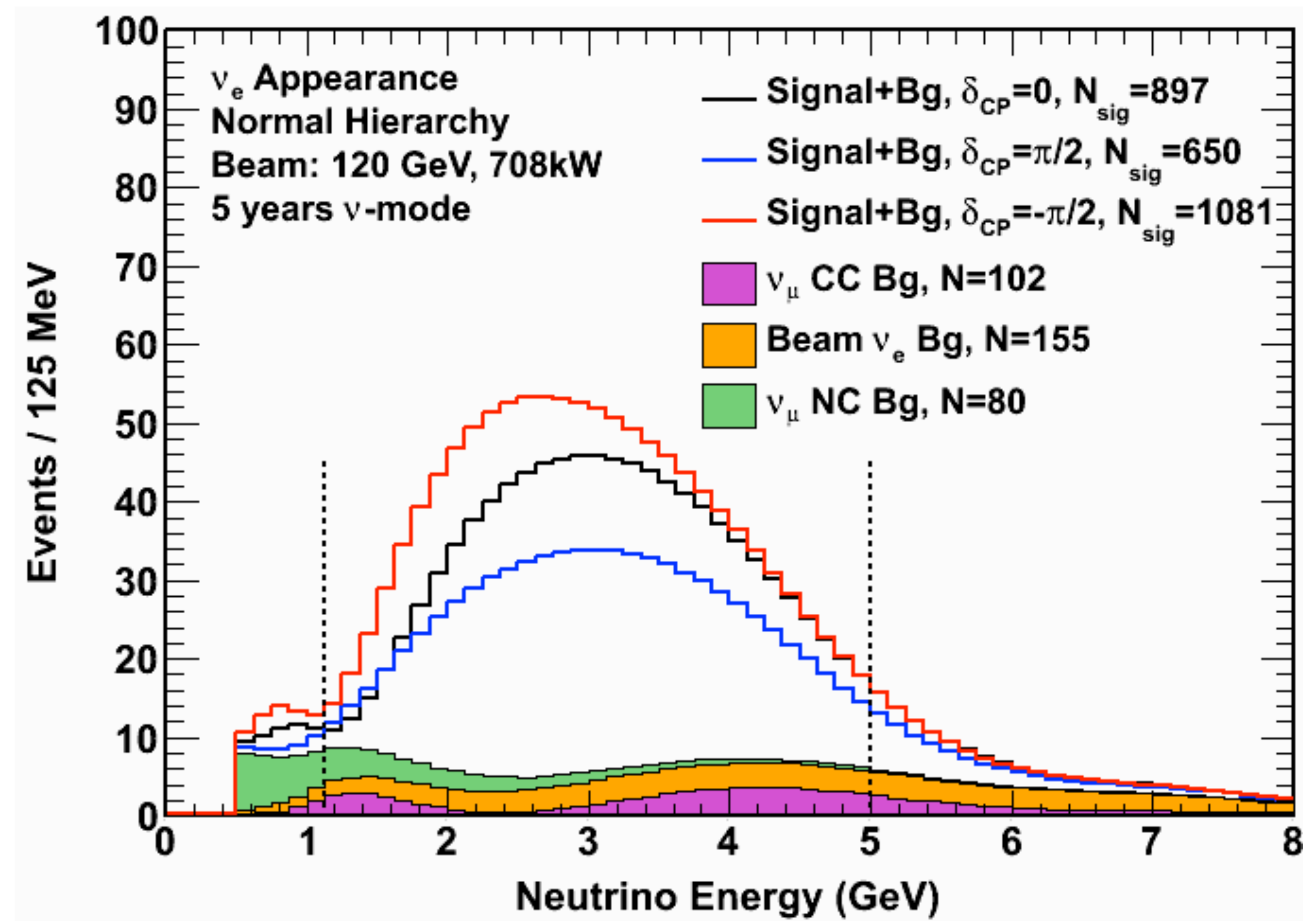
- LBNE's sensitivity to *CP* violation improves with PIP-II:





- With higher power, LBNE will profit from flexible energy choice of neutrino beam:

Z. Isvan (BNL)



- PIP-II increases the power for Booster and MI experiments × 1.6.

Neutrinos

PIP
PIP-II
PX

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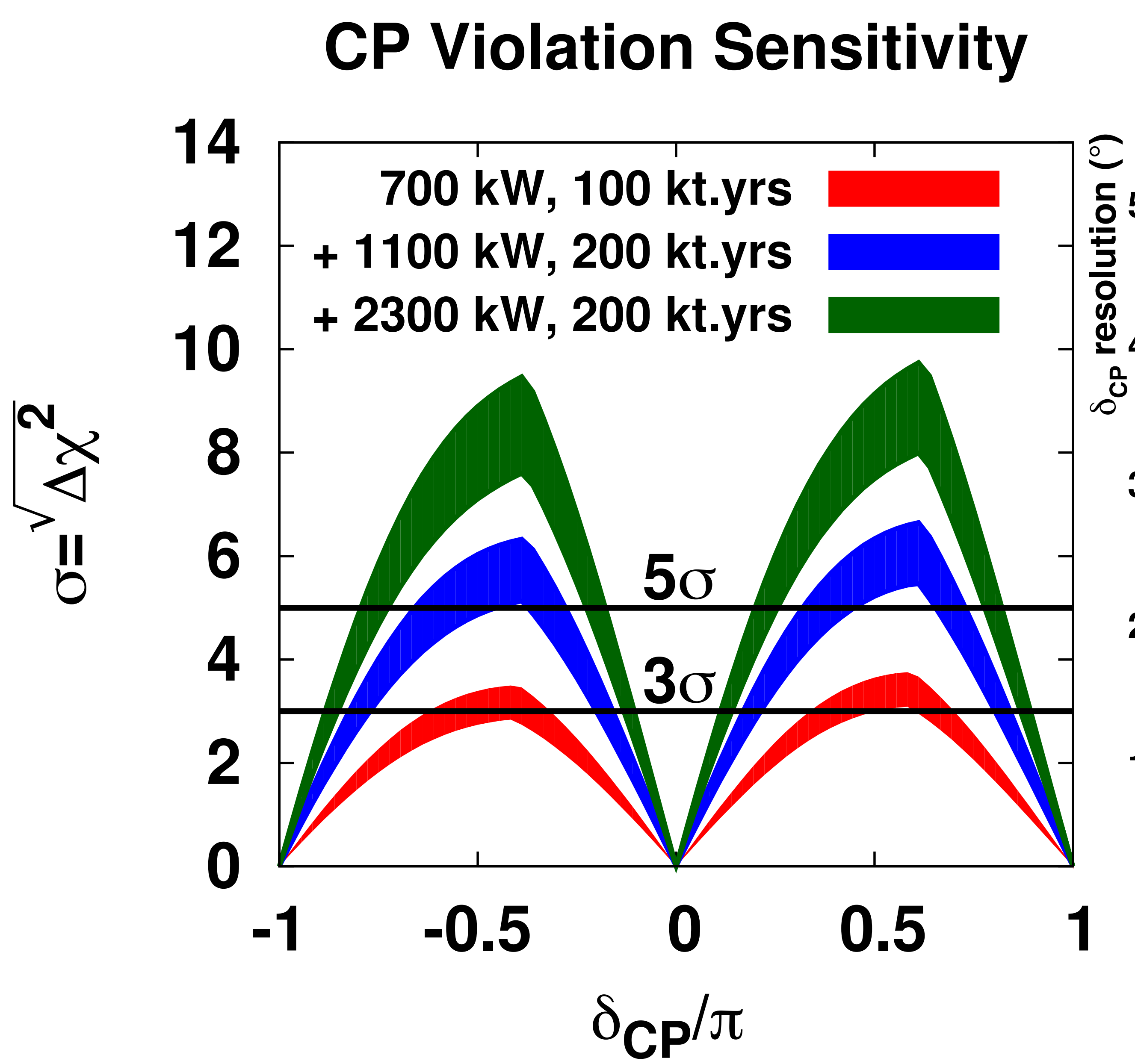

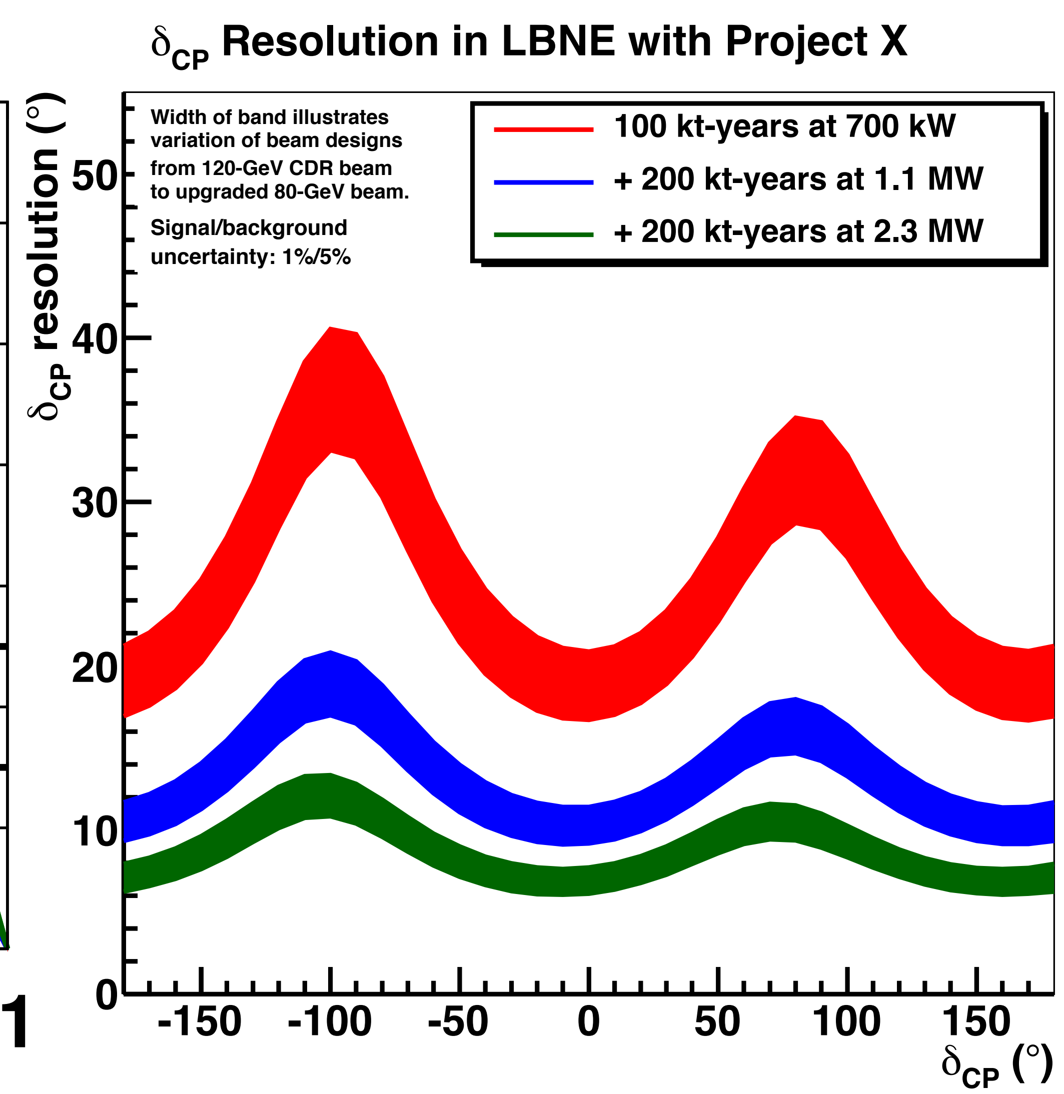

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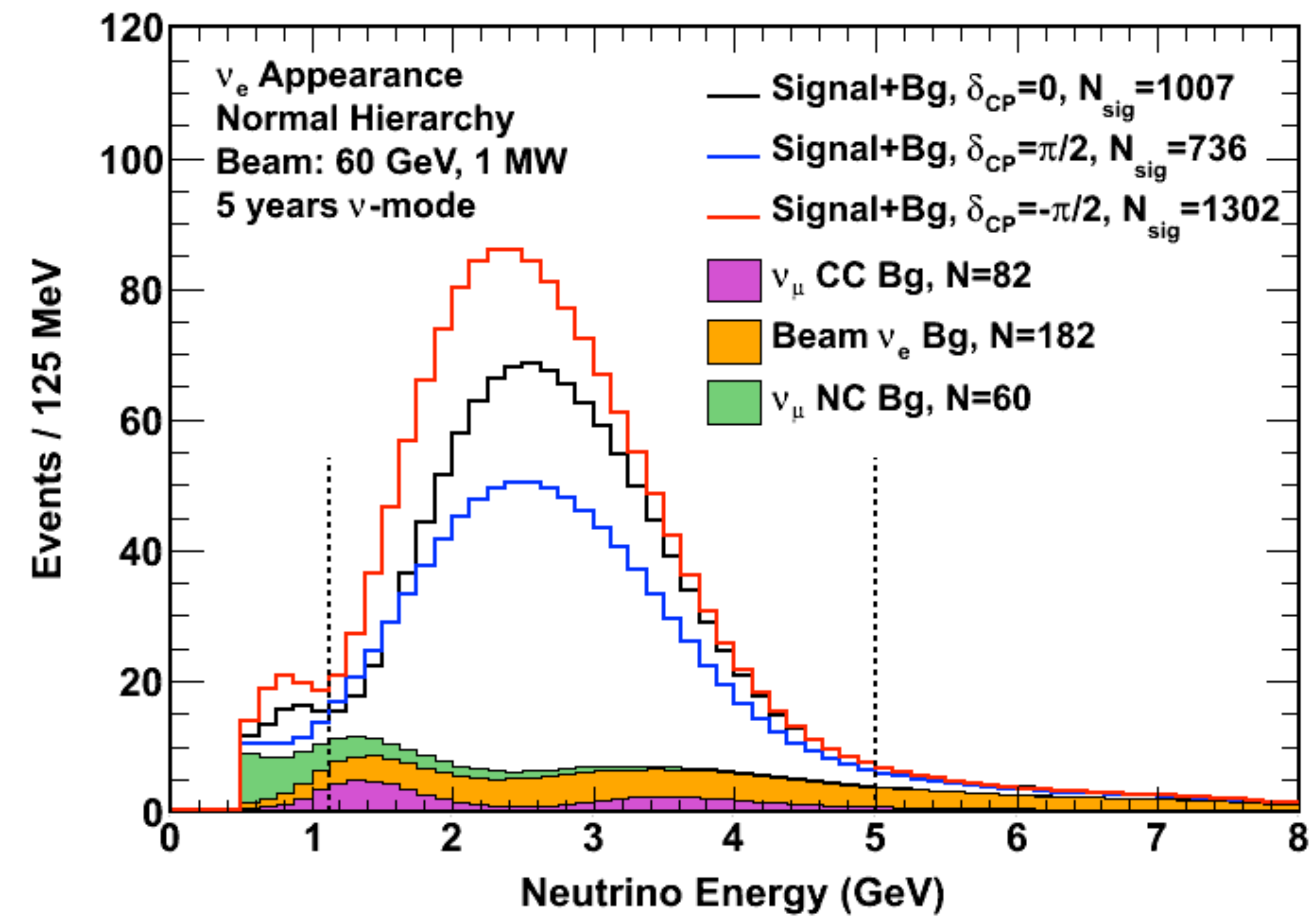

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Non-Standard Neutrino Interactions

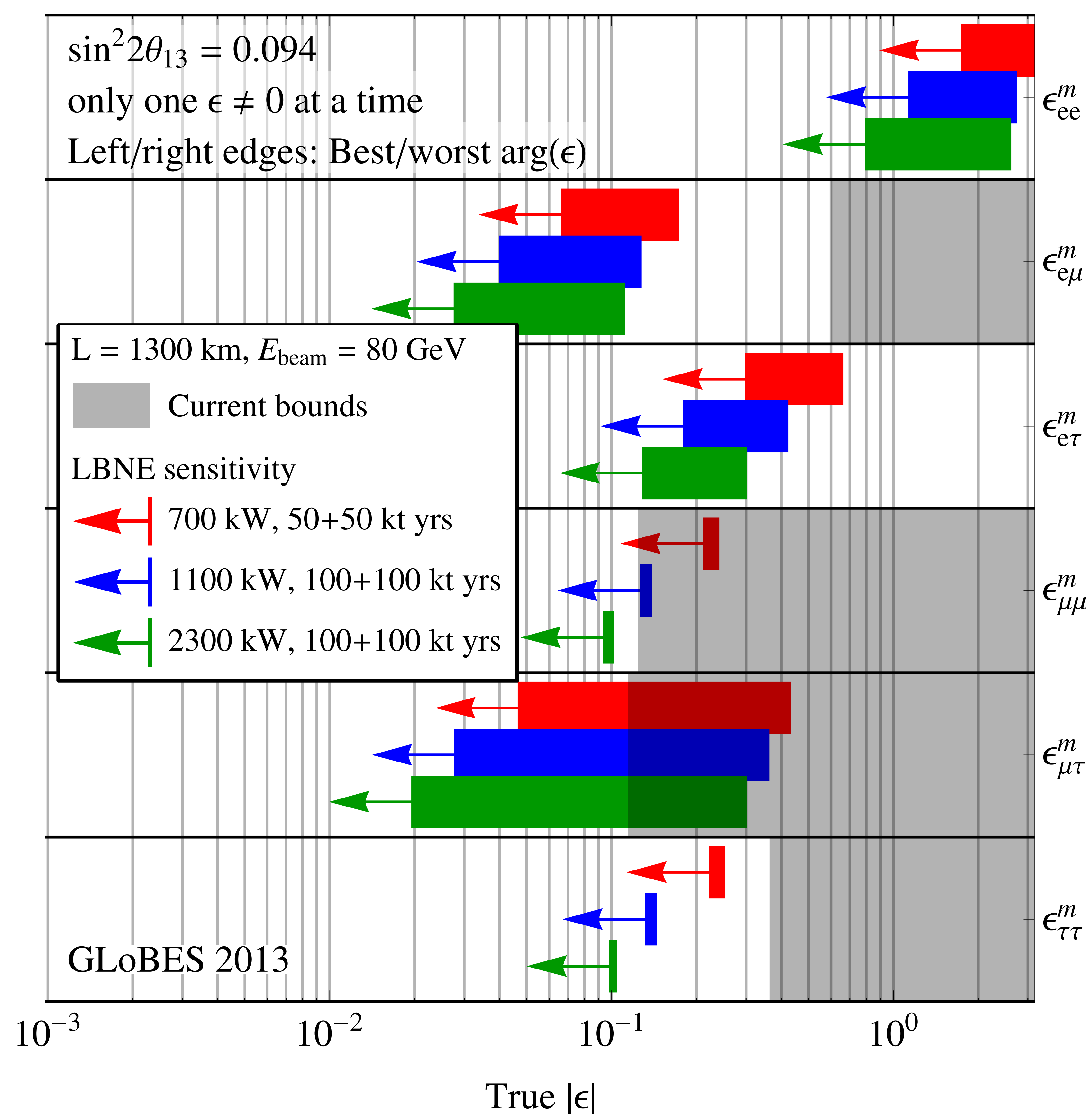
- If neutrinos interact w/ matter via non-Standard interactions (e.g., Z'), their propagation becomes:

$$H = \frac{1}{2E} U \begin{pmatrix} 0 & & \\ & \Delta m^2_{21} & \\ & & \Delta m^2_{31} \end{pmatrix} U^\dagger + \tilde{V}_{\mathrm{MSW}}$$

$$\tilde{V}_{\mathrm{MSW}} = \sqrt{2} G_F N_e \begin{pmatrix} 1 + \varepsilon^m_{ee} & \varepsilon^m_{e\mu} & \varepsilon^m_{e\tau} \\ \varepsilon^{m*}_{e\mu} & \varepsilon^m_{\mu\mu} & \varepsilon^m_{\mu\tau} \\ \varepsilon^{m*}_{e\tau} & \varepsilon^{m*}_{\mu\tau} & \varepsilon^m_{\tau\tau} \end{pmatrix} \text{``} = G_{\mathscr{O}}\text{''}$$

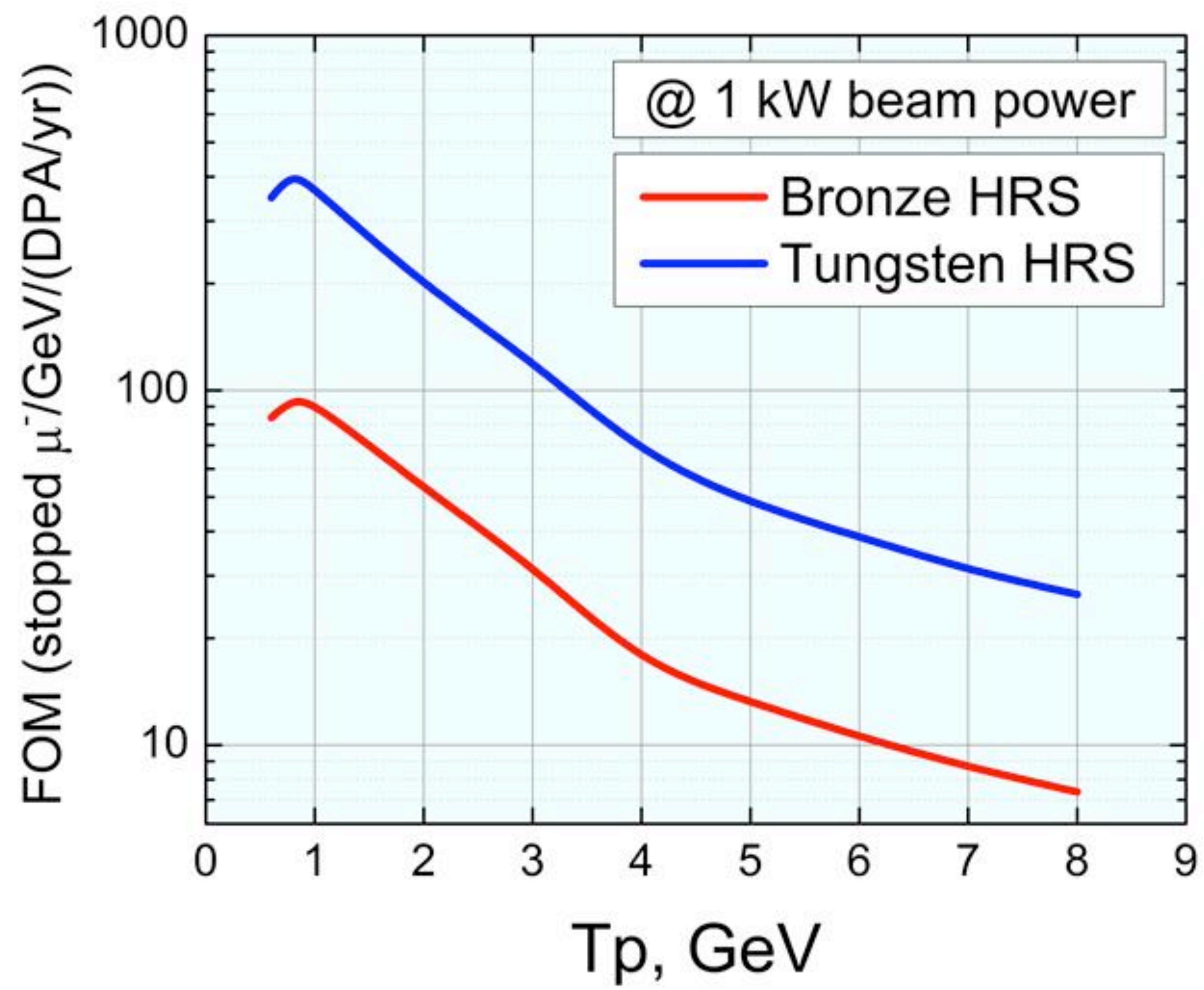
- Distortions in ν_μ disappearance could be sign of mixing with Kaluza-Klein neutrinos.

NC NSI discovery reach (3σ C.L.)



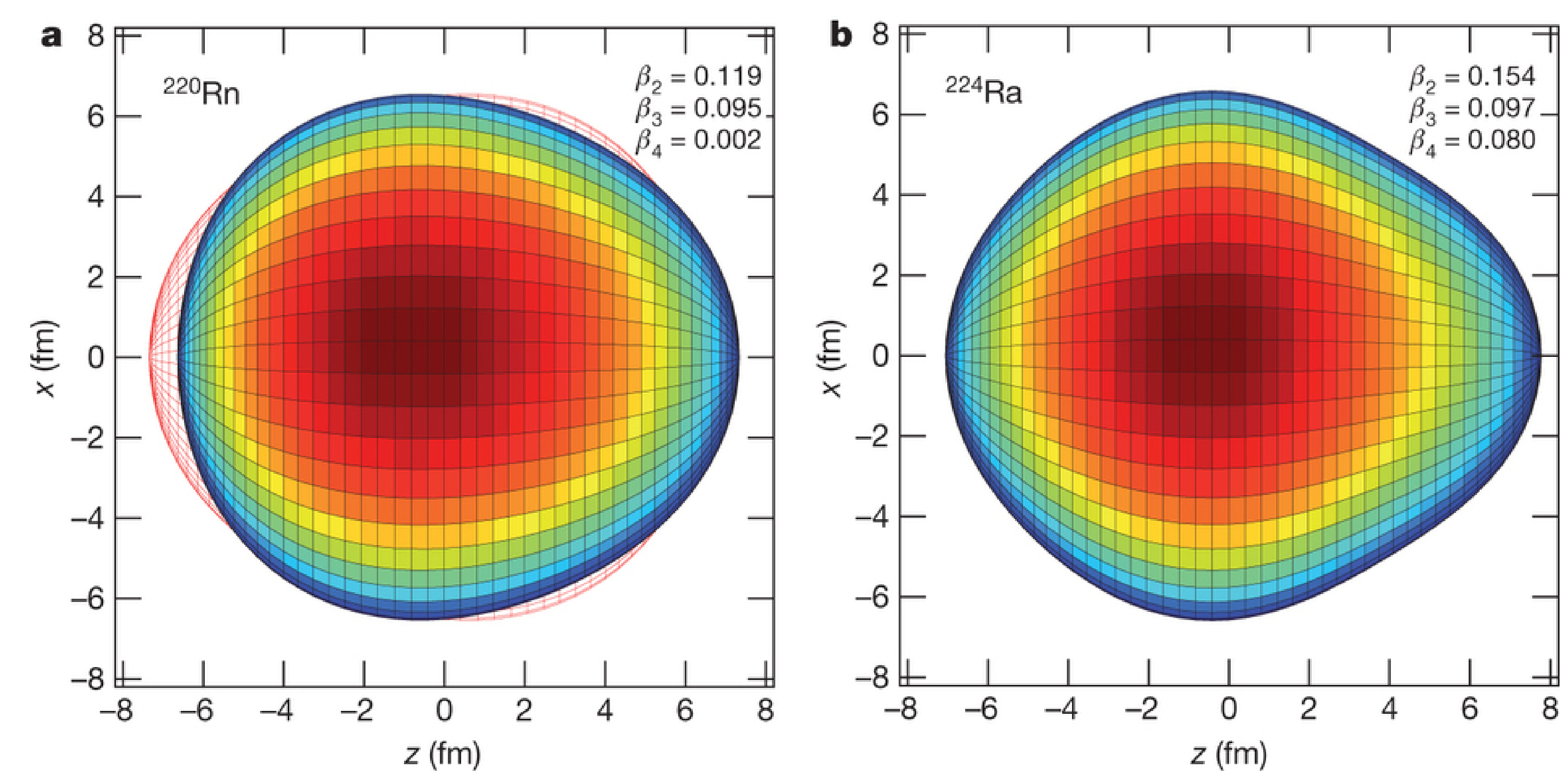
Muons: different beam energy for $\mu \to e$, *etc*.

- PIP-II CW would increase power to Mu2e × 10.
- Lower proton energy eliminates antiproton background.
- Lower energy beam produces less heat in production target: kinder to solenoid.
- Enables runs on many target nuclei:
  - different sensitivity [hep-ph/0203110].
- CW allows different bunch structures:
  - larger nuclei capture muons quickly, so tolerate shorter bunch spacing.



Other Possibilities with PIP^n Intensity

- Short baseline neutrino research: νSTORM, NuMaX, …..
- CLFV processes: $\mu \to e\gamma$, $\mu \to eee$, muonium-antimuonium oscillations.
- Muon magnetic moment with μ^- instead of μ^+.
- Neutron-antineutron oscillations.
- Electric dipole moments with
  - p, or even μ, in a storage ring;
  - n, ^{225}Ra, ^{223}Rn, ^{211}Fr from a spallation target—octupole enhancement.
- First plank in a platform for neutrino factory, muon collider, even VLHC.



Summary

- With PIP Fermilab has increased its intensity for NOvA.
- But higher power from PIP-II is essential for LBNE and very desirable for Mu2e.
- With New Muon g–2, these expts anchor vibrant US program in accelerator-based HEP.
- At the intensity frontier, the key is a powerful, flexible accelerator that can drive many simultaneous experiments.
- A series of proton improvement projects at Fermilab would provide such flexibility.
- Suite of possible experiments allows the portfolio to wax and wane with budget vagaries.

Steve Holmes and the PIPs

Backup Slides

One Slide Answers

Discoveries from rare processes and precision physics

- Discovery of the electroweak scale: $2^{1/2}G_F = g^2/M_W^2 = v^{-2} = (246\ \text{GeV})^{-2}$.
- Flavor physics: muon, strangeness, two neutrinos, third generation. Who ordered that?
- Neutrinos are massless.
- CP violation.
- Charged currents of all kinds; high suppression of FCNC.
- Hints of/evidence for charm, weak bosons, top, Higgs before real production feasible.
- Neutrinos are not massless after all.

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Theoretical uncertainties in muon g–2

- The discrepancy expt–SM is huge: larger than the electroweak contribution. But is it QCD?
- Two contributions: HVP (dominant but firm), HLbL (subdominant but squishy).
  - HVP tension between extraction from $e^+e^- \to$ hadrons *vs*. hadronic τ decay.
- General success of and specific work from lattice QCD makes clear than it will weigh in on HVP tension and eventually surpass the other methods. Spacelike vs. timelike.
- HLbL is a much more difficult problem: still at the idea (theory) and R&D (computing) stage.
  - several groups engaged in simpler calculations that could shed light on model estimates of HLbL, e.g., $\pi\gamma\gamma$ vertex, related to Primakoff-effect experiments.

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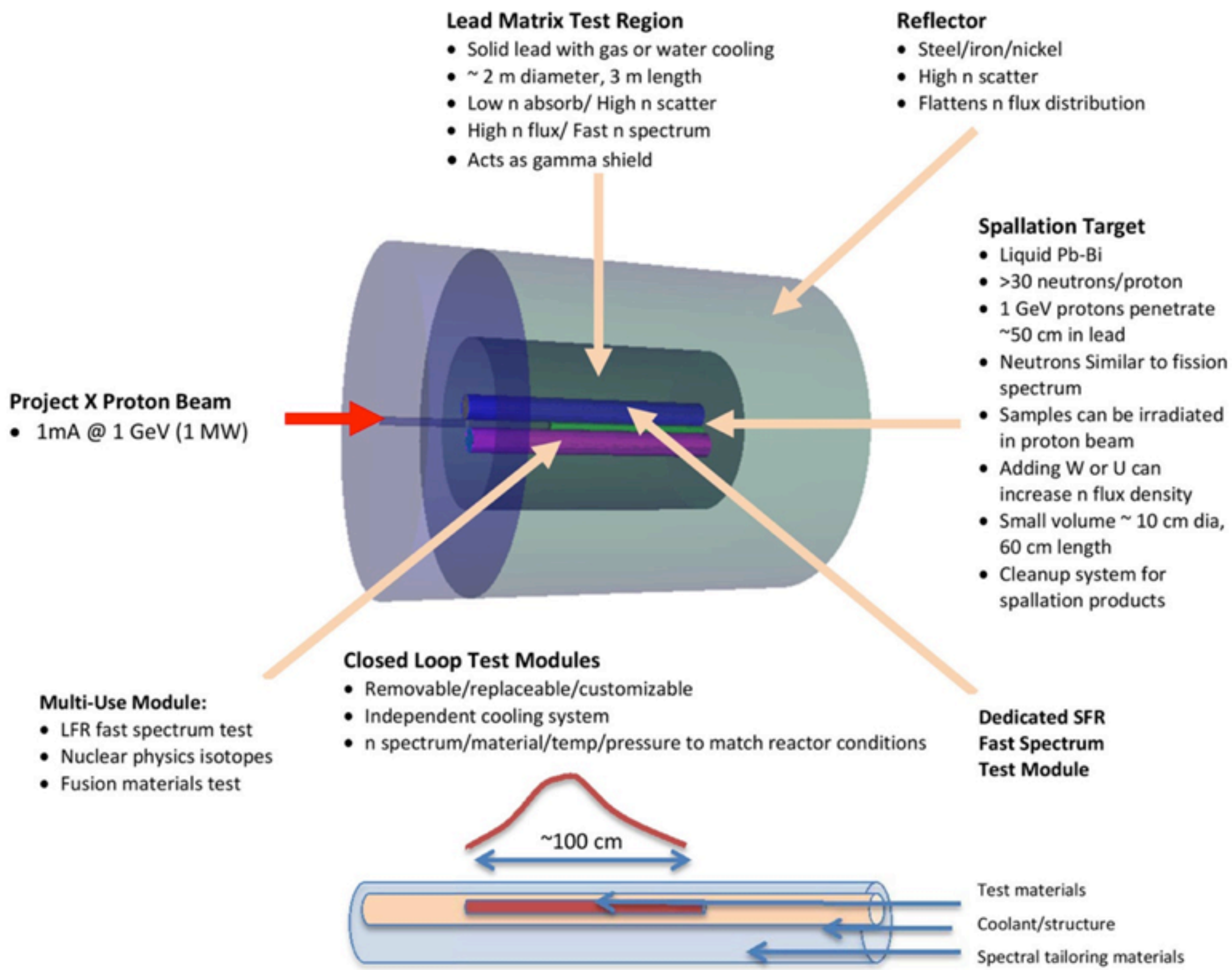
Spallation Target for Fundamental Physics

- SNS (ESS) is (may be) oversubscribed.
- Fundamental physics waits for other disciplines.
- Aim would be to design a target optimized for EDMs (Ra, Rn, Fr), (u)cold *n*, energy applications.



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